Analysis of electro-conductive properties of textile materials for use as electrodes

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In the paper the research of flat textile products for use as electrodes was presented. To determine the suitability of textile materials, resistance measurements were carried out. Based on the received results of studies different types of textile electrodes were designed. Textile electrodes tests were caried out on human phantoms. The electro-conductive properties of human forearm phantom were also described. Based on these results special electro-conductive hydrogels with electro-conductive particles were feasible. The hydrogel is an important element of the forearm's phantom model of a survey of electrodes for muscle electrostimulation. The hydrogel is equivalent to human skin and tissue. The hydrogel should have a permanence and repetition of the electro-conductive properties.
Key words: *electro-conductive textiles, resistance measurement, textile electrodes, electrostimulation, forearm phantom, hydrogel*

1. Introduction

The electro-conductive flat textile products are may be occur especially in medical applications such as: systems monitoring physiological parameters [1], or for bioimpedance spectroscopy [2], textile sensors for cardiac monitoring [3, 4], textile electrodes [5] and another [13, 14]. Electrotherapy is an important part of physical therapy, which is used for medicinal purposes in various types of electrical stimuli. Accordingly, applied electric current can cause a therapeutic effect of a stimulus and analgesic (neuromuscular stimulation, pain-killing, improvement of tissue perfusion, decreased muscle tone, easing inflammation, accelerate the absorption of edema, improve metabolism, tissue regeneration etc.) [6-8]. In the framework of the project under the name „Textronic system to electrical stimulation of muscles" implemented under the Operational Programme Innovative Economy, work on the optimal design of the textile electrodes intended for electrostimulation of muscles is carried out. The textile electrodes are the new product which can replace the traditional metal or graphite electrodes. They are elastic and good fitted to body shape (legs or arms). At the same time they do not give feelings of discomfort or oppression, and they are more friendly to the patient. Especially they can be used to muscles electrostimulation during the therapy. The electrodes require studies proving its usefulness. In order to test the textile electrodes model mapping impedance properties of forearm's phantom was constructed. In order to construct a phantom it is necessary to know the electroconductive properties of human forearm. The properties can be assess on the basis on measurements of surface resistance of the skin and its capacity. These quantities depend on skin moisture, electrolyte, thickness of the epidermis and individual human characteristics etc. On-going studies are an important contribution to the development of a new area of engineering knowledge named textronics, which combines three areas: textiles, electronics and computer science [9].

2. Materials and methods

Flat textile products for the textile electrodes should not cause patient's allergic reaction. The textile materials should have a good electrical conductivity. Moreover an important is the stability of the textile electrodes for a long-term measurements. For study electro-conductive textile samples consist of different electro-conductive particles were selected, Tab.1.

The measure of electro-conductive properties of textiles is the resistance. To determine the resistance four-point probe technique was used [10]. For this purpose textile samples of seventy millimeters square were prepared. Electric scheme for resistance measurement is shown in Fig.1 and 2. Four brass electrodes were located at sample surface so close to edges as possible. Two adjacent electrodes were powered by a precision current source. DC Power Supply Agilent E3644A (range: 0-8 V and 8 A) as ammeter was used. Between the other two electrodes voltage drop was measured. Multimeter Agilent 34410A (6½ Digit, range: 0-1000 V) as voltmeter was used. The pressure of a single electrode on the sample was 23 kPa.

Thus the horizontal resistance (1) and vertical resistance (2) was obtained:

$$R_h = \frac{U_h}{I_h} \qquad (1)$$

and

$$R_v = \frac{U_v}{I_v} \qquad (2)$$

3. Results of resistance measurements of textile samples

The choice of textiles for the electrodes requires analysis of the electro-conductive properties of the material. The criteria for selecting the optimum textile material for the construction of the electrode was proposed [11]. It is assumed that the order of the criteria is important. The first criterion assumes that the measured resistances not exceed 100 Ω. This condition results from the need to reduce power losses at the electrode. It can make the heat generated in the textile electrodes. The second criterion assumes that the relative expanded uncertainty of measured resistances not exceed 12 %. The preliminary studies have shown that the relative expanded uncertainty of resistance can be up to several percent. The assumed value is based on conducted experiments. The third criterion assumes that the difference between the horizontal and vertical resistances is relatively small. It was assumed that:

Considering the extreme case let R_h £ R_v and R_v = 100 Ω. Then the ratio D is 0.3 for R_h = 77 Ω. It means that the biggest difference between horizontal and vertical resistances, which can occur, is 23 Ω. This value is satisfactory.

The resistance measurements were carried out at ambient conditions: temperature of 24.5 ^{o}C, relative humidity of 36 %.The samples were acclimated under the same conditions. Time after which the voltage drop between other electrodes was reading was 30 seconds. Measurements were repeated three times. The values of average horizontal and vertical resistances of textile samples and relative expanded uncertainty of the resistances are compile in Tab.2. The significance level of 0.05 was assuming. Moreover type B evaluation of standard uncertainties was performed assuming the uniform distribution.

The horizontal resistance changed from 4.33 Ω to 2445.83 Ω. The vertical resistance changed from 1.13 Ω to 230.79 Ω. The relative expanded uncertainty varied widely from 10 % to 58 %, which results from the textile structure [11].

The research showed that all the subsequent criteria satisfy three textile materials:

- knitted fabric containing silver fibres of resistances R_h=45.16 Ω and R_v=52.13 Ω;
- woven fabric containing silver fibres of resistances R_h=20.22 Ω and R_v=15.26 Ω;
- woven fabric made of PES and nickel metalized of resistances R_h=46.48 Ω and R_v=37.91 Ω.

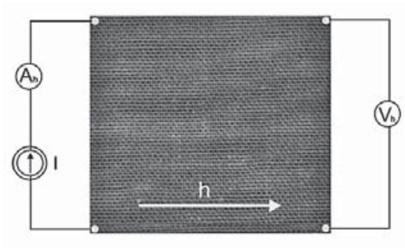


Fig.1 Electric scheme for horizontal resistance measurement [11]

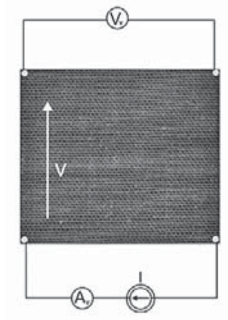


Fig.2 Electric scheme for vertical resistance measurement [11]

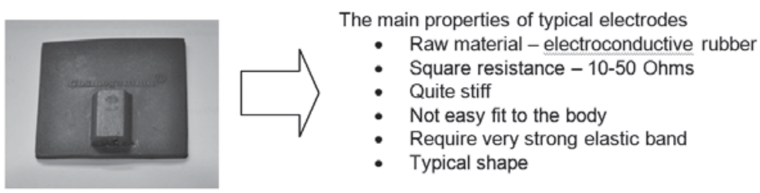


Fig.3 View of typical rubber electrodes

Tab.1 Electro-conductive textile samples

	Kind of textile material	Material	Surface mass	Thickness
No.	-	-	g/m^2	mm
1	Woven fabric	Metallized nylon (Sn, Cu, Ag)	82	0.07
2	Woven fabric	Silver fibres	76	0.19
3	Woven fabric	Silver fibres	149	0.41
4	Woven fabric	PES/ Nickel metallized	155	0.30
5	Woven fabric	PES/ Nickel metallized	65	0.17
6	Woven fabric	PES/ Nickel metallized	83	0.09
7	Woven fabric	PES/ Nickel metallized	152	0.32
8	Knitted fabric	Silver fibres	135	0.55
9	Knitted fabric	Silver fibres	109	0.39
10	Knitted fabric	Silver fibres	134	0.37
11	Knitted fabric	Silver monofilaments	47	0.29
12	Knitted fabric	Silver fibres	128	0.47
13	Non-woven fabric	Graphite fibres	64	0.40
14	Non-woven fabric	PES/ Nickel metallized	251	1.75

4. Design of the new textile electrodes

Metal or rubber electrodes are commonly used in electrotherapy treatment (Fig.3).

The alternative is textronic electrical systems with the textile electrodes. These electrodes are made of electroconductive textile material and they are an integral part of the clothing structures such as shirts or socks.

The three criteria satisfied electroconductive textiles such as knitted fabric made of silver fibres, woven fabric made of silver fibres and nickel metalized woven fabric made of PES. The chosen electro-conductive textile materials were used to the manufacture of prototype textile electrodes. The microscopic photos of selected fabrics are presented in Tab.3. The Basic parameters are described in Tab.1, row 3, 4 and 8.

The elastic bandage was used as the base of construction and as the element of clothing structures. The polyurethane foam of the 3 mm thickness was used as the filling. The size of electrode was 35 mm x 35 mm, where the active electrostimulation surface was 30 mm x 30 mm. The peripheries of electrode were made from electro-conductive yarns.

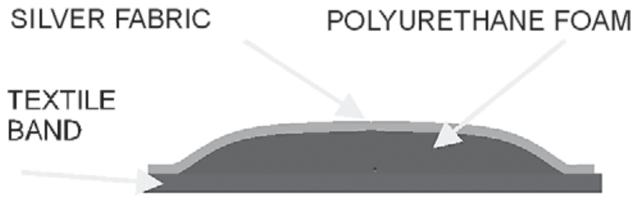


Fig.4 The scheme of elementary electrode [4]

This kind of construction obtains uniformly supply of stimulation current. The scheme of single electrode is presented in Fig.4.

The new idea is to create the few textile electrodes in one clothing structures – matrix electrode. The electrodes can be connected in many ways, which increases the sites undergoing stimulation therapy. The particular elementary electrodes in the matrix electrode have got laminar structures. There were used different methods like sawing and embroidery method to electrode construction. The simplified scheme of matrix electrode is presented in Fig.5. The matrix electrode consists of six elementary electrodes. The elementary electrode was distributed on square of the size 100 mm x 120 mm.

Fig.5 The simplified scheme of prototype textile matrix electrode connected with special medical generator (A); the photo of realization prototype textile matrix electrodes (B) [11]

5. Concept of the electroconductive properties of forearm's phantom

Phantom is designed to study manufactured, new textile electrodes. In the design of the project is expected to make the phantom in the form of a cylinder. The inner part of the cylinder will be filled with hydrogel of impedance close to the average impedance of soft tissue and bones of the human forearm (Fig.6). The forearm's phantom is to ensure the stationarity of parameters. Textile electrodes can be placed on the phantom in different ways, depending on the type of therapy. They can be placed on the surface of the forearm and then the stimulation signal is the surface current. If electrostimulation is a cross-current that penetrated skin, soft tissue and bone, that the electrodes are placed on the opposite side of the forearm. The phantom model assumes that the average surface resistance of hydrogel will be similar to the average surface resistance of the human forearm. Moreover, it is important that the distributions of surface resistance and capacitance in the case of the hydrogel and forearm were comparable. The distributions should not diverge from one another significantly, meet the selected criteria. Generally the phantom imitates impedance properties of human limbs.

Tab.2 Results of resistance measurements of textile samples

Horizontal resistance (Ω)	4.33	41.94	20.22	113.17	46.48	85.19	77.18	358.61	45.16	57.94	67.19	86.43	2445.83	12.36
Relative expanded uncertainty of horizontal resistance (%)	12	12	12	11	12	12	12	13	12	20	12	12	41	16
Vertical resistance (Ω)	1.13	23.06	15.26	34.57	37.91	20.98	46.78	4.83	52.13	230.79	103.50	35.68	10.00	59.34
Relative expanded uncertainty of vertical resistance (%)	12	12	12	10	12	12	12	10	12	20	12	12	58	16

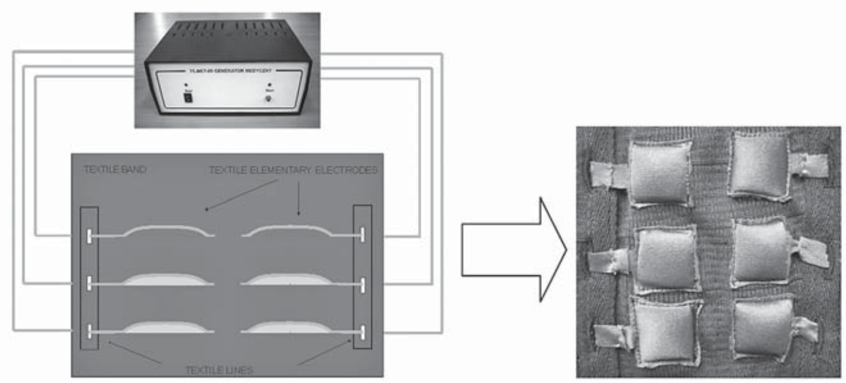


Fig.5 The simplified scheme of prototype textile matrix electrode connected with special medical generator (A); the photo of realization prototype textile matrix electrodes (B) [11]

The schematic view of total measurement stand presents Fig.7.

The forearm phantom consists of a cylinder with glass pipe inside. The pipe is full of water which flows and heats phantom to temperature of human body. The glass pipe imitates properties of human's bone. It is covered with piece of hydrogel that imitates electroconductive properties of soft tissue of limb. Temperature of phantom is stabilized around the value of human body temperature by control system. The system consists of virtual controller which was built in Lab View. The humidity of outside cover of cylinder is kept by the hydrogel which has special property of moisture maintaining.

6. Electroconductive properties of human skin

In the first stage the skin impedance measurements which components resistance and capacitance were carried out. The direct measurement method and RLC meter was used (Fig.8a). The research was conducted for DC current and three kind of frequency 100 Hz, 1 kHz and 10 kHz. Another measurement based on indirect method (Fig.8b) where two outer electrodes (E1, E4) were connected to the generator and another two (inner) electrodes were connected to oscilloscope (measurement devices). All measurements were carried out on volunteers. The electrodes were displacement in constant distance on right human's forearms.

In measurements the electrodes made of medical polyethylene foam were used. They are well arranged along the natural curves of the body. The chosen electrodes are repeatedly used. They can be unstick and dislocated on different measurement placed on human skin. In presented measurement each electrodes were used once. The resistance measurements obtained using the direct method is presented in Tab.4.

The next stage of research was measurement impedance according to indirect method (oscilloscope). This method is come from simplification model of human skin, presented in Fig.9. The resistance R_s is a result of existence extracellular fluid and R_1 is a result of intracellular fluid and C is skin capacity.

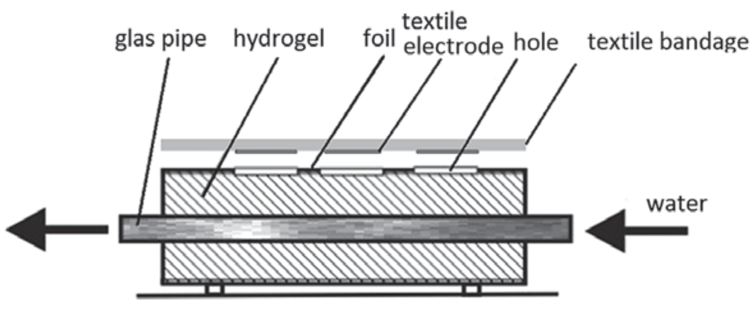
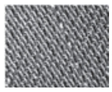


Fig.6 The simplified diagram of the forearm's phantom, the measurement part for textile electrodes – hydrogel with gap for textile electrodes [12]

Tab.3 The microscopic photo of selected electroconductive textile materials [11]

Knitted fabric (silver fibres) – No 8	Woven fabric (silver fibres) – No 3	Woven fabric (PES/Nickel metallized) – No 4
		

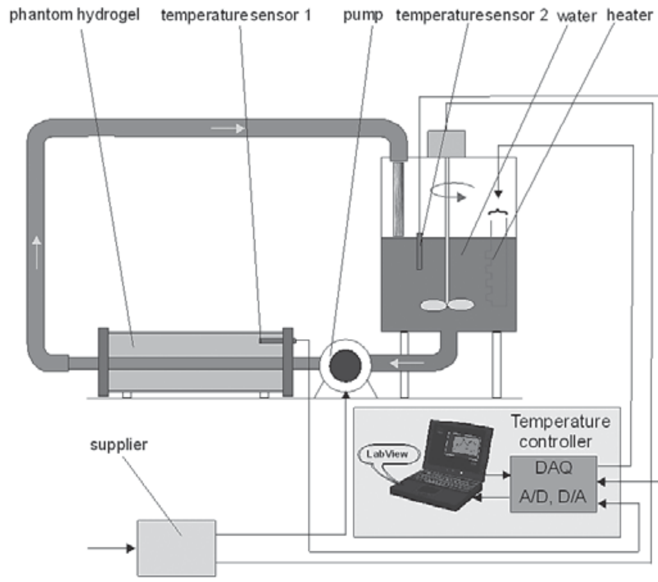


Fig.7 The simplification of forearm's phantom scheme [12]

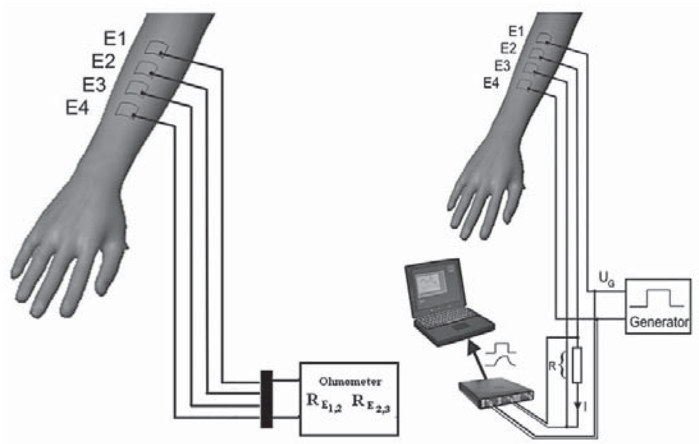


Fig.8 The simplification of measurement stand scheme: a) direct method, b) indirect method [12]

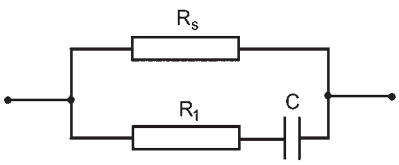


Fig.9 Substitute scheme of human skin [2, 3, 15]

The step function had got 5,2 V. The voltage level was selected in accordance with doctors instructions. In the same time it was recorded the voltage from two inner electrodes. The example of voltage step function and the current response presents Fig.10 and real course presents Fig.11.

The following values are on the Fig.10:

I_{smak} – the maximal value of human skin,

I_P – the transition current,

I_{SU} – the steady current value,

$T = R_1C$ – the time constant,

U_G – the generator voltage.

Based on equation:

$$R_s = \frac{U_G R}{U_R} \tag{4}$$

where: U_R – the voltage drop on resistance R,

R – the resistance to measurement current, and

$$I_P(t) = I_P\ e^{-\frac{t}{T}} \tag{5}$$

Human skin resistance R_s and R_1 according to the model from Fig.9 was calculated. The example of average value of resistance obtained from second method for one man is R_s = 346 Ω and R_1 = 88 Ω, C= 127 nF.

Based on received result authors took the trial to created special hydrogels with different electroconductive particles. They took the assumptions that the average value of resistance should be the similar in 30 % of variation

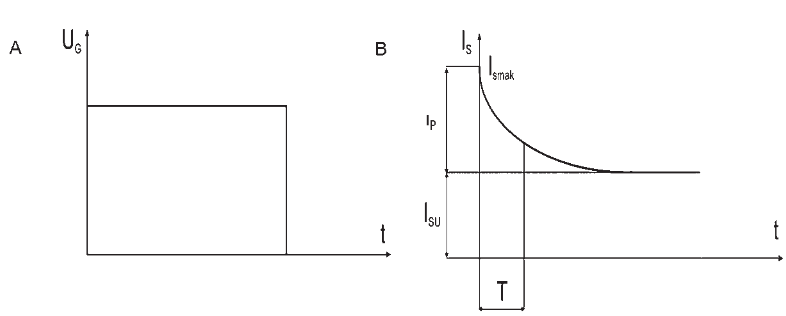


Fig.10 The example of measurement results received using indirect method: A - stimuli impulse, B - the voltage answer [12]

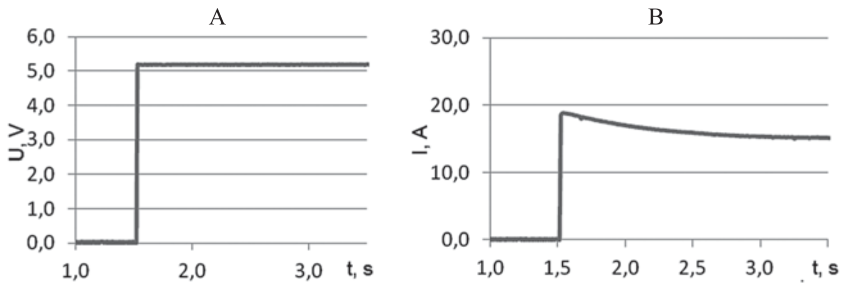


Fig.11 The step function of voltage (A), the current response (B) register on forearm

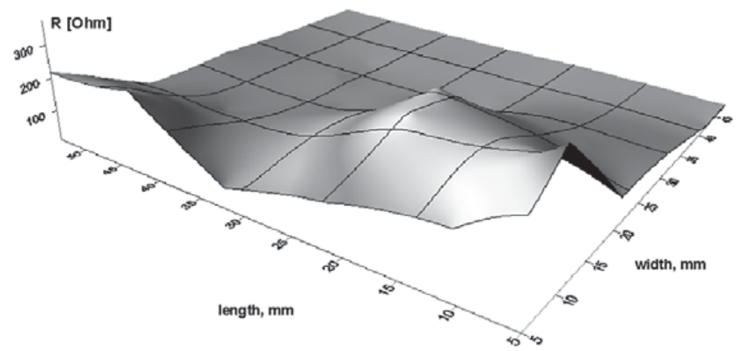


Fig.12 The chosen map of resistance distribution on the surface of the hydrogel containing carbon particles [12]

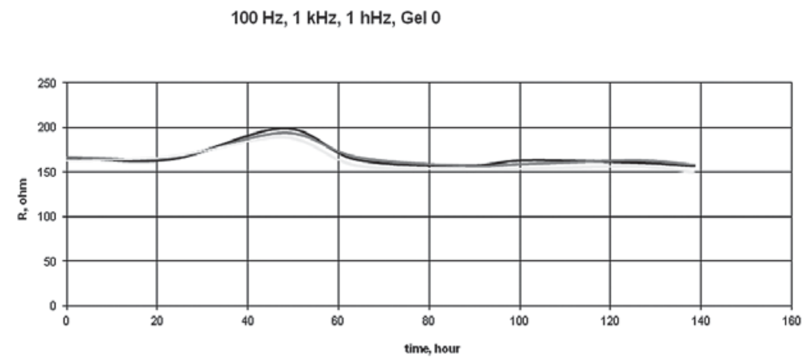


Fig.13 The long time measurements of hydrogels resistance [12]

Tab.4 The average value of human limb resistance - direct method

Parameter	Electrodes		
	$E_{1,2}$	$E_{2,3}$	$E_{3,4}$
Distance between electrodes (cm)	5	5	5
Resistance (Ω)	131	212	107

and the resistance distribution on the hydrogels surface should be uniform. Fig.12 shows a map of resistance R distribution on the surface of the chosen hydrogel containing carbon particles.

It was also conducted long time research during the 140 hours. The measurement received results for three samples of hydrogels presents in Fig.13. The measurement were done also for three different frequency of measurement. To the research Escort ELC – 3133A meter was also used.

7. Conclusions

Textile materials for electrostimulation should have a good electrical conductivity. The most important parameter, from textronic's point of view, is resistance of textile surface. There are many methods of determining the surface resistance. The useful method is four-point probe technique. However, it requires modification and needs to be adapted to the textile objects. The identification of textile material resistance should be aware of the impact of various quantities on the measurement results.

The authors have designated the new criteria for the selection of textile materials for textronic product for muscle electrostimulation. The chosen electro-conductive textile materials were used to design the prototypes of electrodes for muscles electrostimulation. Particularly noteworthy is a matrix electrode which is a new concept of textronic system extending medical applications. Textile electrodes fit well to the shape of the treated limb. This results influence on reduction of the transition resistance between the electrode and the skin. This may affect the improvement of therapy.

Prototype of textile electrode used in muscles electrostimulation has to be tested on a special model. This model should imitate electroconductive properties of muscles. The textile electrode requires a lot of research that enables to identify its properties. Based on research of electroconductive properties of human forearm special electroconductive hydrogels with carbon particles were chosen. Selected hydrogels are an important part of the forearm's phantom. The most important properties of selected hydrogels are resistance. The average value of this quantity is 175 Ω which corresponding with resistance value on human skin. The long time test show satisfy stationary resistance parameters.

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